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Parametric study on thermal performance of earth-to-air heat exchanger used for cooling of buildings

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ABSTRACT

A transient one-dimensional model was developed for studying the thermal performance of earth-to-air heat exchangers (EAHE) for summer cooling under the Algerian Sahara. The effect of extremities was also taken into account. The model validation against both theoretical and experimental data of other researchers showed a good agreement. In addition, a detailed sensitive study was carried out in order to investigate the influence of geometrical and dynamical parameters on the thermal performance of EAHE. Results showed that the air outlet temperature decreases with increasing of pipe length but it increases with increasing of pipe cross section and air velocity. However, the daily mean efficiency increases when the length of pipe increases but it decreases when the cross section area of pipe or air velocity increases. It is also observed that the coefficient of performance drops quickly with increasing of air velocity. Considering as reference the thermal performance of EAHE under steady state conditions, the investigation of Derating Factor reveals that the thermal performance of EAHE in transient conditions is more influenced by the variation of operating duration, pipe diameter and air velocity.

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1. Introduction

The Earth-to-Air Heat Exchanger (EAHE) is a subterranean cooling system that consists in a length of pipe or network of pipes buried at reasonable depth below the ground surface. Ventilation air supply is passed through the pipes and the difference in temperature between the pipe surface and the air drives the heating/cooling of ventilation air. The magnitude of heat exchange between air and pipe is dependent on factors such as, soil temperature, air temperature, pipe dimensions, air flow rate, pipe burial depth and soil and pipe thermal properties.

The main advantages of EAHE system are its simplicity, high cooling and pre-heating potential, low operational and maintenance costs, saving of fossil fuels and related emissions. Pre-heated fresh air supports a heat recovery system and reduces the space heating demand in winter. In summer, in combination with a good thermal design of building, the EAHE can eliminate the need for active mechanical and air-conditioning units in buildings, which will result in a major reduction in electricity consumption of

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Nomenclature

COP	coefficient of performance
Cp	specific heat (J/kg °C)
D	diameter (m)
hc	convective heat transfer coefficient (w/m² K)
L	pipe length (m)
M	mass (kg)
ṁ	mass flow rate of air through the buried pipe (kg/s)
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
U	overall heat transfer coefficient (w/m² K)
v	air velocity (m/s)

Greek letters

η	mean efficiency
Δp	pressure drop (Pa)
Δx	spatial increment in the flowing direction (m)
ρ	density (kg/m3)
λ	thermal conductivity (w/m °C)

Subscripts

a	air
amb	ambient air
(e)	at the inlet of EAHE
i	interior
o	outside
s	disturbed soil
soil	undisturbed soil
(s)	outlet
t	pipe
tot	total

building if the EAHE is designed well. A literature review reveals that various theoretical and experimental studies [1–8] have been conducted on the EAHE under different climatic conditions in order to improve its cooling and heating potential. Among these works, it is useful to quote the following:

Al-Ajmi et al. [9] developed an analytical model of earth-to-air heat exchanger (EAHE) for predicting the air outlet temperature and cooling potential of these devices in a hot and arid climate. In this model, the thickness of disturbed soil is taken equal to the radius of buried pipe and the thermal resistance of pipe material is neglected. After validation with other published experimental works, this model was integrated within the TRNSYS environment in order to investigate the thermal performance of typical dwelling coupled to an EAHE in Kuwait climatic conditions. It was found that the EAHE can provide 30% of cooling energy demand in the summer season. A new design of passive cooling system consisting in a solar chimney (SC) joined together with an EAHE was carried out by Maerefat et al. [10]. The results showed that this system with a proper design can provide a thermally comfortable indoor environment for a large number of hours in the scorching summer days. Another study was conducted by Nayak et al. [11] on a different configuration formed from a photovoltaic-thermal \collector (PV/T) and an EAHE for greenhouse heating. It was observed that the greenhouse inside temperature increased by around 7-8 °C during winter season at night. Yildiz et al. [12] studied an experimental system for greenhouse cooling consisting in an earth-to-air heat exchanger assisted by a solar photovoltaic system (PV). The experiment was performed at the Ege University, Izmir, Turkey.

Using a one-dimensional transient analytical model, Cucumo et al. [13] studied the influence of burial depth on the thermal performance of EAHE systems. This model permitted also to predict the temperature fields of air inside the pipe and of soil surrounding the buried pipe, taking into account the thermal perturbation of upper free surface and the possible phase change (condensation) in the buried pipes. A similar model was developed by Su et al. [14] for studying a deeply EAHE used for building energy saving. The proposed model was validated against experimental data. Chel et al. [15] performed a thermal analysis of vault roof building integrated with an earth-to-air heat exchanger (EAHE). Experimental results showed that the room air temperature during winter increased by about 5–15.8 °C compared to the outdoor air temperature while it decreased within the same interval during summer months.

Furthermore, a transient three-dimensional heat transfer model based on the coupled conservation equations of energy for the soil and the circulating air is presented by Gauthier et al. [16] for studying the thermal behavior of soil heat exchanger-storage systems (SHESSs) applied to reducing the energy consumption of greenhouses. The effect of various design and operating parameters on the performance of SHESSs was also investigated. Tittelein et al. [17] presented a numerical model for earth-to-air heat exchangers integrating the response factors method and a finite elements approach for resolving the tow-dimensional conduction problem. Kumar et al. [18,19] developed two different numerical models; one based on Finite Difference Method for estimating the energy saving potential of earth-air heat exchanger system. It was taken into account the humidity variations of circulating air in this model. The second leaned on the concept of Artificial Neural Network aims to conceive a computer design tool which can help the designer to evaluate any aspect of earth-to-air heat exchanger and behavior of final configuration. Zhang et al. [20] developed a numerical method consisting in an Artificial Neural Network based on Heat Convection (ANN- HC) algorithm for predicting the local average Nusselt Numbers along the pipe. Then this algorithm was integrated with a transient three-dimensional heat transfer model based on finite element analysis for studying the heat conduction in the ground domain surrounding the EAHE.

In addition, Thiers et al. [21] presented a study conducted on two-dwelling passive building in Formerie (North-West of France) using the dynamic simulation software COMFIE in which a new developed module has been integrated in order to account for the implemented ventilation system, including a heat recovery unit and an earth-to-air heat exchanger. Lee et al. [22] developed a new module which is integrated and implemented in the EnergyPlus program for the simulation of EAHE and a sensitive analysis was carried out to investigate the effect of design parameters such as pipe radius, pipe length, air flow rate and pipe depth on the overall performance of earth tube under various conditions during cooling season. Bansal et al. [23] and Vaz et al. [24] carried out numerical studies based on computational fluid dynamics (CFD) by the help of FLUENT environment for predicting the heating and cooling capacity of earth-air-pipe heat exchanger systems.

The main objective of this article is to present an investigation of earth-to-air heat exchanger (EAHE) used for cooling of building under the climatic conditions of Algerian Sahara. This study was performed on July where the demand of energy for cooling is at